

Charge Exchange X-ray Emission of M82: $K\alpha$ triplets of O VII, Ne IX, and Mg XI

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ABSTRACT

Starburst galaxies are primary feedback sources of mechanical energy and metals, which are generally measured from associated X-ray emission lines assuming that they are from the thermal emission of the outflowing hot gas. Such line emission, however, can also arise from the charge exchange X-ray emission (CXE) between highly ionized ions and neutral species. To understand the feedback of energy and metals, it is crucial to determine the origin of the X-ray emission lines and to distinguish the contributions from the CXE and the thermal emission. The origin of the lines can be diagnosed by the $K\alpha$ triplets of He-like ions, because the CXE favors the inter-combination and forbidden lines, while the thermal emission favors the resonance line. We analyze the triplets of O VII, Ne IX, and Mg XI observed in the *XMM-Newton* reflection grating spectra of the starburst galaxy M82. The flux contribution of the CXE is 90%, 50%, and 30% to the O VII, Ne IX, and Mg XI triplet, respectively. Averaged over all the three triplets, the contribution of the CXE is $\sim 50\%$ of the total observed triplet flux. To correctly understand the hot outflow of starburst galaxies, it is necessary to include the CXE. Based on the measured CXE contributions to the O VII, Ne IX, and Mg XI triplets, we estimate the relative abundances of O, Ne, and Mg of the outflow and find they are similar to the solar ratios.

Key words: atomic processes – plasmas – ISM: jets and outflows – ISM: abundances – galaxies: starburst – galaxies: individual: M82 – X-rays: ISM

1 INTRODUCTION

Starburst galaxies are the primary sources that eject energy and metals into the intergalactic medium. The properties of the outflow are fundamental to the understanding of the feedback process of galaxies. The energy and metals of the outflow are generally measured from the X-ray emission, particularly emission lines, associated with starburst galaxies. In past studies, the X-ray emission lines are assumed to come from the hot outflow itself, the temperature and metal abundances of which are extracted based on thermal models.

The X-ray line emission, however, can arise not only from the hot gas, but also from the interaction between the hot gas and the neutral cool gas. For example, when the solar wind interacts with a comet, the highly ionized ions in the wind can readily pick up electrons from the neutral species of the comet. The product ions remain highly ionized and are left in excited states. They will emit X-ray photons when they decay to ground states. This process is called charge exchange X-ray emission (CXE, also called

charge transfer) and explains the bright cometary X-ray emission (e.g. Lisse et al. 1996; Cravens 1997, 2002). It can be represented by:

$$A^{q+} + N \rightarrow A^{(q-1)+} + N^+, \quad (1)$$

where a highly ionized ion A^{q+} (like O VIII, Ne X) picks up an electron from a neutral species N (like H, H₂), producing an excited ion $A^{(q-1)+}$, which will emit X-ray photons when it decays to the ground state. For the historical studies and recent developments of the CXE, we refer to Dennerl (2010) and references therein.

Different from the thermal emission, the CXE contributes only emission lines. If the X-ray line emission, or part of it, is due to the CXE, the measurement of the thermal and chemical properties of the hot outflow based on thermal-only models will be misleading. To correctly understand the hot outflow, it is crucial to reveal the origin of the X-ray emission lines and to distinguish the contributions from the CXE and the thermal emission.

Based on the tight spatial correlation of H α and X-ray emissions, Lallement (2004) speculated the importance of the CXE between the hot outflow and the cool halo gas for starburst galaxies. From Suzaku and *XMM-Newton* observations of the cap above the

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disk of M82, Tsuru et al. (2007) showed a marginal detection of an emission line at 0.459 keV, which may be due to the CXE of CVI ($n = 4 \rightarrow 1$). From *XMM-Newton* EPIC spectra of the central region of M82, Ranalli et al. (2008) also reported two lines (around 10 and 16 Å), which can not be adequately accounted for by thermal models and may be contributed by the CXE from neutral Mg and O VII.

One diagnostic that can be used to determine the origin of the X-ray emission lines is the $K\alpha$ triplet between $n = 2$ shell and $n = 1$ ground state of He-like ions, which consist of a resonance line, two inter-combination lines, and a forbidden line (for a recent review, see Porquet et al. 2010). For a thermal plasma, the electron collisional excitation is efficient and favors the resonance line, while for the CXE, the de-excitation favors the triplet states and thus the inter-combination and forbidden lines. Therefore, the line ratios of the triple can determine the origin of the X-ray emission lines. If the forbidden line dominates, the CXE will be the most feasible origin, because the hot plasma is already highly ionized and photonization is negligible.

In this letter we analyze the $K\alpha$ triplets of He-like ions of O VII, Ne IX, and Mg XI of M82 observed by *XMM-Newton* Reflection Grating Spectrometers (RGS, den Herder et al. 2001). M82 is one of the nearby brightest galaxies in X-ray and regarded as a prototypical starburst. A bipolar outflow originated from the nuclear starburst extends beyond 5' (about 5 kpc) from the disk (e.g., Stevens et al. 2003). Ranalli et al. (2008) have analyzed the *XMM-Newton* RGS O VII triplet of M82 and they fitted three Gaussians to the blended triplet. They showed that the line intensity ratios are marginally consistent with the CXE. In this letter, we decompose the triplets into the CXE and the thermal emission using the laboratory measured CXE spectrum of O VII triplet. As a result, we can quantify the contribution of the CXE to the observed $K\alpha$ triplets of He-like ions, including O VII, Ne IX, and Mg XI. The RGS also allow us to study the O VII triplet at different spatial regions.

The local emissivity of the CXE of one particular line (assuming single electron capture) $P_c \propto n_{Aq+} V \sigma n_{neu}$, where n_{Aq+} , n_{neu} , V , and σ denote the ion density, the neutral density, the relative velocity, and the charge exchange cross section, respectively. If we know the CXE fluxes of the O VII, Ne IX, and Mg XI triplets, we can estimate the relative abundance of O, Ne, and Mg with the temperature information. It provides important insight to the composition of the hot outflow, especially when the assumption of the thermal-only origin of the X-ray line emission is poor. We will make a first attempt to estimate the relative abundances of O, Ne, and Mg using the CXE fluxes of their He-like triplets.

The paper is structured as follows. We describe the observation data in §2. The analysis results are presented in §3. Our conclusion and discussion are given in §4. Errors are given at 1 σ confidence level.

2 OBSERVATION DATA

We use four archival *XMM-Newton* RGS observations of M82, the obs-IDs of which are 0112290201, 0206080101, 0560590201, and 0560590301. The total effective exposure time is ~ 120 ks after removing intense flare periods, which doubles the useful dataset used by Ranalli et al. (2008). The most recent version of Science Analysis System (SAS, 10.0) is used for the reduction of photon events. In these observations, the RGS slit is generally not parallel to the outflow direction and the extracted emission lines are broadened due to the tilt of the outflow. Thus we limit our extraction to

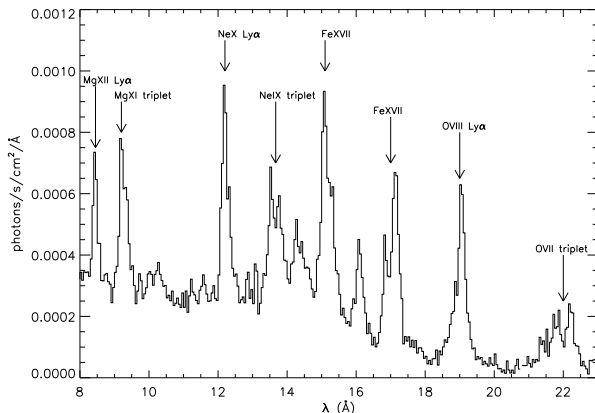


Figure 1. Fluxed *XMM-Newton* RGS spectrum of M82 extracted from the central 30'' radius of the cross-dispersion direction. Both RGS1 and RGS2 are combined together. The spectrum is dominated by Ly α lines of H-like and He-like states of O, Ne, and Mg and neon-like Fe lines. The triplets of O VII, Ne IX, and Mg XI are analyzed below.

events within 30'' radius of the cross-dispersion direction. We also extract the O VII triplet from $-90''$ to $-30''$ and from $30''$ to $60''$ of the cross-dispersion direction, where the O VII triplet is bright enough for further study. For the region larger than $60''$, the O VII triplet is heavily blended by the structures of the X-ray emission and does not allow a simple fitting as we do below, so it is excluded.

There are two RGS on the *XMM-Newton*. CCD4 in RGS2 covering the O VII triplet failed, and CCD7 in RGS1 covering the Ne IX triplet also failed. Thus, the O VII triplet data are from RGS1 and the Ne IX triplet data from RGS2, while the Mg XI data are from both RGS1 and RGS2. The Si XIII triplet around 6.7 Å is neglected here as the effective area is small and the photon counts are too few to obtain robust results.

3 RESULTS

The observed *XMM-Newton* RGS spectrum of M82, corrected for the effective area, is shown in Figure 1. As can be seen, the emission is dominated by Ly α lines of H-like and He-like states of O, Ne, and Mg and neon-like Fe lines. Below we analyze the $K\alpha$ triplets of He-like ions of O VII, Ne IX, and Mg XI. The intensity ratio of resonance, inter-combination, and forbidden lines can tell the origin of the X-ray emission lines.

3.1 O VII triplet

Let's first focus on the observed O VII triplet within the central $-30'' - 30''$ region, which is plotted in the left panel of Figure 2. A continuum interpolated between the line wings has been subtracted. It shows clearly that the forbidden line is stronger than the resonance line. The dominance of the forbidden line can not result from the thermal excitation, but is a signature of the CXE. The laboratory measured CXE of O VII triplet using the spare X-ray microcalorimeter from ASTRO-E (Suzaku) mission (Beiersdorfer et al. 2003) is over-plotted as dashed line in Figure 2. The laboratory measured CXE of O VII triplet fits the observed O VII triplet well.

To quantify the contributions of the CXE and the thermal emission, we fit the observed triplet with two components of the CXE and the thermal emission. The CXE component consists of

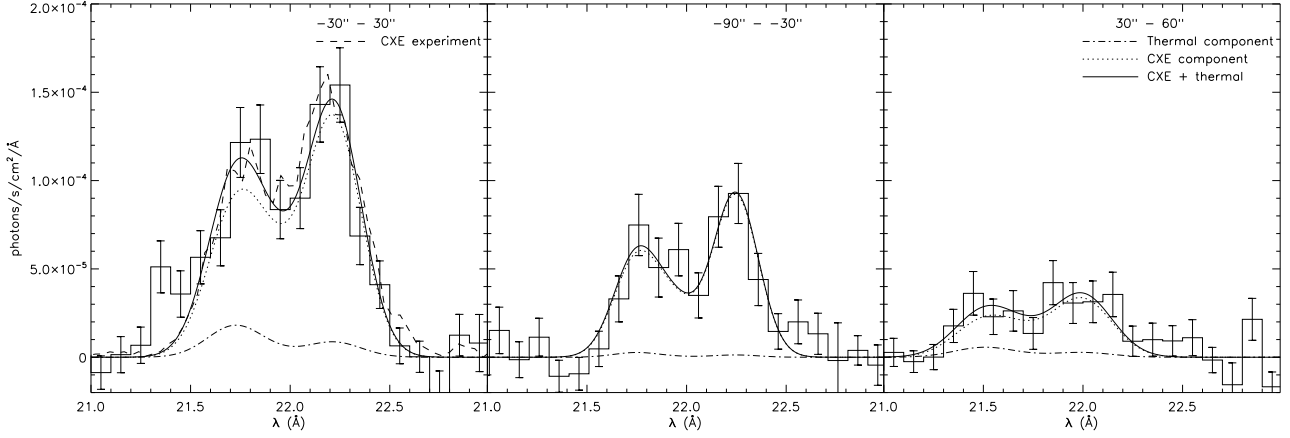


Figure 2. RGS spectra of the O VII triplet in three extraction regions. A continuum, which is calculated as the interpolation between the line wings, has been subtracted. Laboratory data for the CXE of the O VII triplet by Beiersdorfer et al. (2003) is over-plotted as the dashed line in the left panel. The RGS spectrum agrees well with the CXE data. The solid line is the sum of the fitted model of the CXE (dotted line) and the thermal emission (dot-dashed lines). Most of the flux of O VII triplet is due to the CXE.

Table 1. Results of fitting the CXE and thermal emission to the triplets of O VII, Mg XI, and Ne IX.

	$f_c(10^{-5})^a$	$f_t(10^{-5})^a$	$\Delta\lambda(\text{\AA})$	$\sigma_\lambda(\text{\AA})$	χ^2/dof	$r(\text{\AA})$	$i(\text{\AA})$	$f(\text{\AA})$	t_r	t_i	t_f
O VII(-30'' - 30'')	8.6±1.3	1.0±1.2	0.12±0.02	0.14±0.01	7.0/6	21.6	21.8	22.1	0.624	0.070	0.306
O VII(-90'' - -30'')	4.9±0.9	0.1±0.9	0.15±0.01	0.11±0.01	6.4/6	21.6	21.8	22.1	0.624	0.070	0.306
O VII(30'' - 60'')	2.3±0.8	0.3±0.8	-0.1±0.05	0.15±0.03	5.2/6	21.6	21.8	22.1	0.624	0.070	0.306
Mg XI	2.6±1.4	7.1±1.5	0.03±0.006	0.05±0.005	11.1/9	9.17	9.23	9.31	0.587	0.101	0.312
Ne IX($\frac{N_{\text{Fe}}}{N_{\text{Fe}}} = 1.5^b$)	5.1±1.2	5.7±1.0 ^c	0.06±0.007	0.06±0.006	10.2/8	13.45	13.55	13.7	0.138	0.027	0.076
Ne IX($\frac{N_{\text{Fe}}}{N_{\text{Fe}}} = 4^b$)	4.6±1.4	6.5±1.2 ^c	0.06±0.008	0.06±0.007	11.5/8	13.45	13.55	13.7	0.262	0.052	0.144

Note: for the meaning of symbols, see eq. (2); ^a f_c and f_t are in units of photons/s/cm²; ^b $\frac{N_{\text{Fe}}}{N_{\text{Fe}}}$ is in units of the solar ratio; ^cthe value f_t of Ne IX is for the thermal emission of both Ne IX triplet and Fe XIX lines.

three Gaussians centered on the triplet lines, the ratios of which are fitted to the laboratory measured CXE triplet by Beiersdorfer et al. (2003). The thermal component also consists of three Gaussians, the ratios of which are calculated at $T = 8 \times 10^6$ K, which is the estimated temperature of the hot gas (see §3.2). The modeled spectrum can be written as

$$f_{\text{model}} = \frac{1}{\sqrt{2\pi}\sigma_\lambda} \sum_{j=r,i,f} (f_c c_j + f_t t_j) \exp \left[-\frac{(\lambda - \lambda_j - \Delta\lambda)^2}{2\sigma_\lambda^2} \right], \quad (2)$$

where λ_j is the wavelength of resonance, inter-combination, and forbidden lines, c_j the corresponding ratios for the CXE, t_j the ratios for the thermal emission, f_c and f_t is the flux of the CXE and the thermal emission respectively. The CXE ratios $c_{r,i,f}$ =0.317, 0.149, 0.535; the thermal ratios $t_{r,i,f}$ are calculated using APEC 2.0 (Smith et al. 2001) and listed in Table 1. We assume that the dispersion σ_λ and the wavelength shift $\Delta\lambda$ are the same for both components. Since the observed RGS lines are dominated by the spatial extent of the source, it means that we assume both components are from a similar spatial volume. The fitted results are listed in Table 1 and plotted in Figure 2. The thermal component only accounts for 10±12% of the observed O VII triplet. As the CXE dominates, the results are insensitive to the adopted temperature. For example, if we adopt $T = 5 \times 10^6$ K, the thermal fraction is 11±14%. For higher temperatures, the thermal ratios $t_{r,i,f}$ are almost unchanged

and the results are not affected. Thus we conclude that most of the observed O VII triplet is due to the CXE.

We can estimate the CXE contribution to the observed O VIII Ly α (19 Å) flux within the same region, which is $\sim 1.8 \times 10^{-4}$ photons/s/cm². In §3.2, we will see that the flux ratio of Mg XII Ly α to Mg XI triplet indicates a temperature around 8×10^6 K. At such a high temperature, the ion fraction of O VIII is negligible and O IX ions dominate charge exchange collisions. While it is possible for an O IX ion to capture two electrons to become an O VII ion directly, the cross section of double-electron charge exchange is generally lower than 20% of that of single-electron charge exchange (Greenwood et al. 2001). Thus we consider the case of multiple charge exchange collisions. That is, an O IX ion experiences one charge exchange collision becoming an O VIII ion, then becomes an O VII ion through another collision. As the transition ratio of $n(\geq 3 \rightarrow 1)$ to $n(= 2 \rightarrow 1)$ is measured to be similar for the collision of O IX and O VIII (Greenwood et al. 2001), in the case of multiple collisions, the emission of an O VII-triplet photon is coupled with the emission of an O VIII-Ly α photon. In other words, the CXE flux of O VIII Ly α is the same as that of O VII triplet. Since the fitted CXE flux of O VII triplet is 8.6×10^{-5} photons/s/cm², we expect that about half of the total observed flux of O VIII Ly α is due to the CXE. The CXE contribution to the O VIII Ly α emission will be larger if the assumption of multiple collisions is not fulfilled.

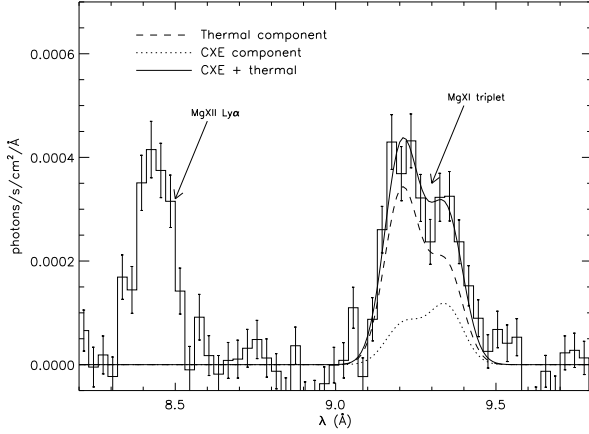


Figure 3. RGS spectrum of the Mg XI triplet. An interpolated continuum has been subtracted. The solid line is the sum of the CXE component (dotted line) and the thermal component (dashed line). The Mg XII Ly α line is also plotted.

The observed O VII triplets from $-90''$ to $-30''$ and from $30''$ to $60''$ are plotted in the middle and right panels respectively. They also show the dominance of the forbidden line. That is, the CXE occurs not only at the starburst nucleus ($\sim 30''$), but also at the outflow regions. The fitted results are listed in Table 1. The different $\Delta\lambda$ reflects the tilt of the outflow relative to the cross-dispersion direction mentioned in §2. The observed O VIII Ly α fluxes of the two regions are 8.6 and 4.9×10^{-5} photons/s/cm 2 respectively. The observed flux ratios of O VII triplet to O VIII Ly α are similar for all three regions, which implies a same scenario of multiple charge exchange collisions.

3.2 Mg XI triplet

The observed Mg XI triplet and Mg XII Ly α line are plotted in Figure 3. Different from the O VII triplet, the Mg XI triplet is dominated by the resonance line, i.e., by the thermal emission. This enables an estimation of the temperature of the hot gas assuming there is no CXE. The ratio (0.57) of the observed flux of Mg XII Ly α line (5.6×10^{-5} photons/s/cm 2) to that of Mg XI triplet (9.7×10^{-5} photons/s/cm 2) implies a temperature of 8×10^6 K. We fit the observed Mg XI triplet with both the CXE and the thermal emission. The ratios $c_{r,i,f}$ of the CXE are assumed to be the same as those of the laboratory measured CXE of the O VII triplet. The ratios of the thermal component are calculated at $T = 8 \times 10^6$ K. The fitted results are plotted in Figure 3 and listed in Table 1. The contribution of CXE is about $30 \pm 15\%$ to the observed Mg XI triplet.

We can perform a self-consistency check on the temperature estimation by taking into account the CXE. The ion fraction of Mg XIII and Mg XII at $T = 8 \times 10^6$ K is 0.28 and 0.44 respectively. In the case of multiple charge exchange collisions, the CXE flux of Mg XII Ly α line is 40% of that of Mg XI triplet. Excluding the CXE flux, the remaining thermal flux of Mg XII Ly α is 4.6×10^{-5} photons/s/cm 2 . The ratio of the thermal flux of Mg XII Ly α to that of Mg XI triplet (7.1×10^{-5} photons/s/cm 2) is 0.65, which corresponds to a temperature of $\sim 8.2 \times 10^6$ K. If single collision happens, the thermal flux of Mg XII Ly α is 4×10^{-5} photons/s/cm 2 , corresponding to a temperature of $\sim 8 \times 10^6$ K. Thus the temperature estimated without the CXE is consistent with that considering the CXE.

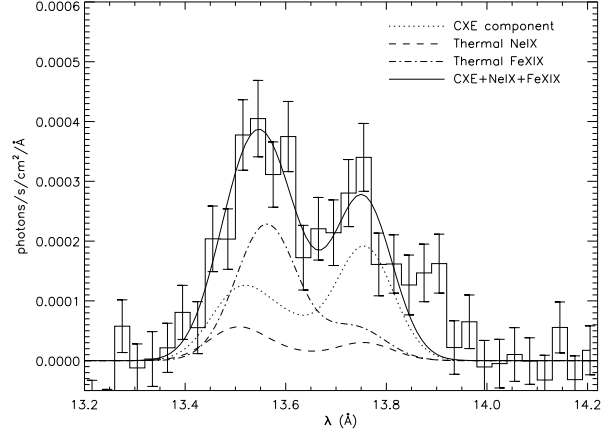


Figure 4. RGS spectrum of the Ne IX triplet. The continuum has been subtracted. The Ne IX triplet is mixed with Fe XIX lines. The solid line is the sum of the CXE (dotted line), the thermal Ne IX triplet (dashed line), and the thermal Fe XIX emission (dot-dashed line).

3.3 Ne IX triplet

The observed Ne IX triplet is plotted in Figure 4. It is similar to the Mg XI triplet (right part of Fig.3). The Ne IX triplet, however, is mixed with Fe XIX lines. At $T = 8 \times 10^6$ K, the Fe XIX lines are comparable to, or even stronger than, the Ne IX triplet. We take into account the Fe XIX lines by including several other Gaussians centered on strong Fe XIX lines. The abundance ratio of Ne/Fe, obtained by Ranalli et al. (2008) from fitting the RGS spectrum assuming thermal-only models, is 1.5 times the solar value (calibrated to Lodders 2003). However, their fitted Mg/Fe ratio is 4 times the solar value. Since Fe is mainly produced in SNe Ia and α -elements are enriched by SNe II, in principle, α /Fe should be similar. Thus we adopt two values (1.5 and 4) for the Ne/Fe ratio. The fitted results are listed in Table 1 and the result of the Ne/Fe ratio of 1.5 is plotted in Figure 4.

We see from Table 1 that the fluxes of the CXE do not change much for the Ne/Fe ratios of 1.5 and 4. This is because the mixing of Fe XIX lines is mainly around the resonance line, the Ne/Fe ratio does have much effect on the relative importance of the resonance and forbidden lines. The CXE flux of the Ne IX triplet ($\sim 5 \times 10^{-5}$ photons/s/cm 2) dominates over the thermal flux of the Ne IX triplet (1.4 and 3×10^{-5} photons/s/cm 2 for Ne/Fe=1.5 and 4 respectively) and accounts for $\sim 50\%$ of the total observed flux.

4 CONCLUSION AND DISCUSSION

We have analyzed the $K\alpha$ triplets of O VII, Ne IX, and Mg XI of the *XMM-Newton* RGS spectra of M82. We show that most of the observed O VII triplet is due to the CXE. The contribution of the CXE is 30% to the Mg XI triplet. Taking into account the mixing of Fe XIX lines, the fitted CXE of Ne IX triplet dominates over its thermal emission. Averaged over all the three triplets, the contribution of the CXE is about 50% to the total observed flux.

As stated in the introduction, the local emissivity of the CXE of one particular line $P_c = (\sum_q f_q n_{A^{q+}}) V \sigma n_{\text{neu}}$, where the sum is over all possible ionization states that can charge exchange to produce the line with an efficiency f_q . We can estimate the relative abundances of O, Ne, and Mg based on the CXE fluxes of their $K\alpha$ triplets. We consider the case of multiple charge exchange collisions.

sions as discussed in §3.1. An additional complication is the foreground absorption. While the column density N_H can be obtained from fitting the whole spectrum as discussed below, here we adopt a column density $N_H = 0.2 \times 10^{22} \text{ cm}^{-2}$, which is taken from Ranalli et al. (2008). Then the absorption factor (f_{abs}) relative to the O VII triplet is 3 and 4.5 for the Ne IX and Mg XII triplet respectively.

We use the relation of the charge exchange cross section $\sigma \propto Z$, where Z is the element number (e.g. Wargelin et al. 2008). We assume the relative velocity is the same for all three elements as their element numbers are similar. We also assume the efficiency of producing the triplet f_q is the same for all three elements. The observed CXE flux of the triplet $f_c \propto n_A f_A Z f_{abs}$, where n_A is the number density for element A and f_A the fraction of both fully stripped and H-like ions for element A. This leads to $n_A \propto f_c / (f_A Z f_{abs})$. Using the fitted f_c in Table 1, we find that the chemical abundance relative to O is 0.16 and 0.06 for Ne and Mg respectively. These ratios are similar to the solar ratios of 0.15 and 0.07, calculated from the solar abundance table of Lodders (2003).

The O abundance of the hot gas of M82 is found to be about 4 times smaller than other α elements in thermal-only models (Read & Stevens 2002; Origlia et al. 2004), which is difficult to explain. However, the abundance ratios of O, Ne, and Mg estimated from the CXE are similar to the solar ratios. Therefore, the low abundance of O obtained from thermal-only models is likely to be a consequence of neglecting the CXE.

As the average contribution of the CXE to the triplets is $\sim 50\%$ and the contribution differs for different lines, the CXE will affect the estimation of the thermal and chemical properties of the hot gas. In previous studies of M82 (e.g., Read & Stevens 2002; Ranalli et al. 2008), multiple-temperature models have been used to fit the observed spectra. The multiple temperatures are likely due to the neglect of the CXE. For example, if neglecting the CXE, the temperature estimated from the observed flux ratio of O VIII Ly α to O VII triplet will be 3.5×10^6 K, which is misleading. To properly estimate the temperature and metal abundances, it is necessary to fit the whole observed spectrum with both the CXE and the thermal emission. For such a task, a detailed model of the spectra of the CXE, including the CXE of Fe XVII is needed. We plan to return to this in a later work.

ACKNOWLEDGEMENTS

We thank Peter Beiersdorfer for kindly providing us the data of laboratory measured CXE of the O VII triplet data, Jifeng Liu for helpful discussions, and our referee for valuable comments. This research has made use of *XMM-Newton* archival data. *XMM-Newton* is an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA).

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